

Measurements of Heavy Elements in ^3He -rich SEP Events

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Abstract. Using the Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE), we have studied the properties of a selection of small ^3He -rich solar energetic particle (SEP) events with heavy ion enhancements in the energy range $\sim 11\text{--}22$ MeV/nucleon. These events contain significantly increased $^3\text{He}/^4\text{He}$ ratios over the solar wind value of 0.0004 in the energy range $\sim 4.5\text{--}5.5$ MeV/nucleon. In order to characterize the events, the following features have been investigated. First, the heavy element content has been measured and compared to that found in past studies of impulsive SEP events. Next, the simultaneous 38–53 keV electron flux, measured with the Electron, Proton, and Alpha Monitor (EPAM) on ACE, has been examined for possible activity near the ^3He -rich event onset times. Finally a list of measured solar X-ray flares, with corresponding H-alpha flares where possible, has been scrutinized for potential correlations with these events. The results show an apparent correlation between event onset and increased electron flux, and a possible association with X-ray flares.

INTRODUCTION

The heavy element content of ^3He -rich SEP events may provide insight into the nature and origin of this type of occurrence. ^3He -rich SEP events were first observed in 1970 by Hsieh and Simpson (1), and their related heavy element enhancements were first noted by Hurford et al. (2). Since 1970, enhancements of ^3He have come to be associated with “impulsive” SEP events, one of the two main classifications of SEP events (impulsive and gradual). Impulsive events, which usually have a duration on the order of several hours, typically contain $^3\text{He}/^4\text{He}$ ratios which are 2–3 orders of magnitude greater than that of the solar wind. In addition, the Fe content of impulsive events is normally ~ 10 times that of the solar wind (3, 4, 5), while the Ne, Mg, and Si abundances are enhanced by a factor of ~ 3 (4, 5). Impulsive events have been associated with $\sim \text{keV}$ electron emission from the Sun (6), as well as with X-ray flares.

Gradual events, on the other hand, have been thought to contain material which reflects closely the composition of the solar wind and corona. However, recent measurements of the composition of gradual events by Mason et al. and Cohen et al. (3, 7) have revealed deviations from coronal abundances toward the impulsive event characteristics described above. Because of these measurements, one can no longer assume that gradual events do not have ^3He enhancements. This complicates the distinction between impulsive and gradual events. The material in

gradual events is understood to have been accelerated out of the interplanetary medium by shocks which are driven by coronal mass ejections. Gradual events, unlike impulsive events, typically have a duration of days.

There are several observational differences between impulsive and gradual SEP events with respect to their composition and accompanying electromagnetic emissions. By examining the heavy element content and coincident solar activity of small ^3He -rich SEP events, it is possible to gain information relevant to the classification of these events and to the origin of the ejected material.

DATA ANALYSIS AND DISCUSSION

Using the Solar Isotope Spectrometer (SIS) (8), a set of eight small ^3He -rich SEP events with heavy element enhancements which occurred between September 6, 1998 and July 12, 1999 have been selected. The events have been defined by the following criteria: (1) The $^3\text{He}/^4\text{He}$ ratio is $\geq 4\%$ in the energy range $\sim 4.5\text{--}5.5$ MeV/nucleon. (2) The heavy element ($Z \geq 10$) flux in the energy interval $\sim 11\text{--}22$ MeV/nucleon is greater than that of the solar quiet time background. (3) Event onset times are chosen to coincide with a rise in the ^3He flux. (4) Event stop times are defined by the return of the heavy element fluxes to background levels, determined by inspection. All eight of the events are shown in Figure 1, including the heavy element counts, ^3He flux, coinci-

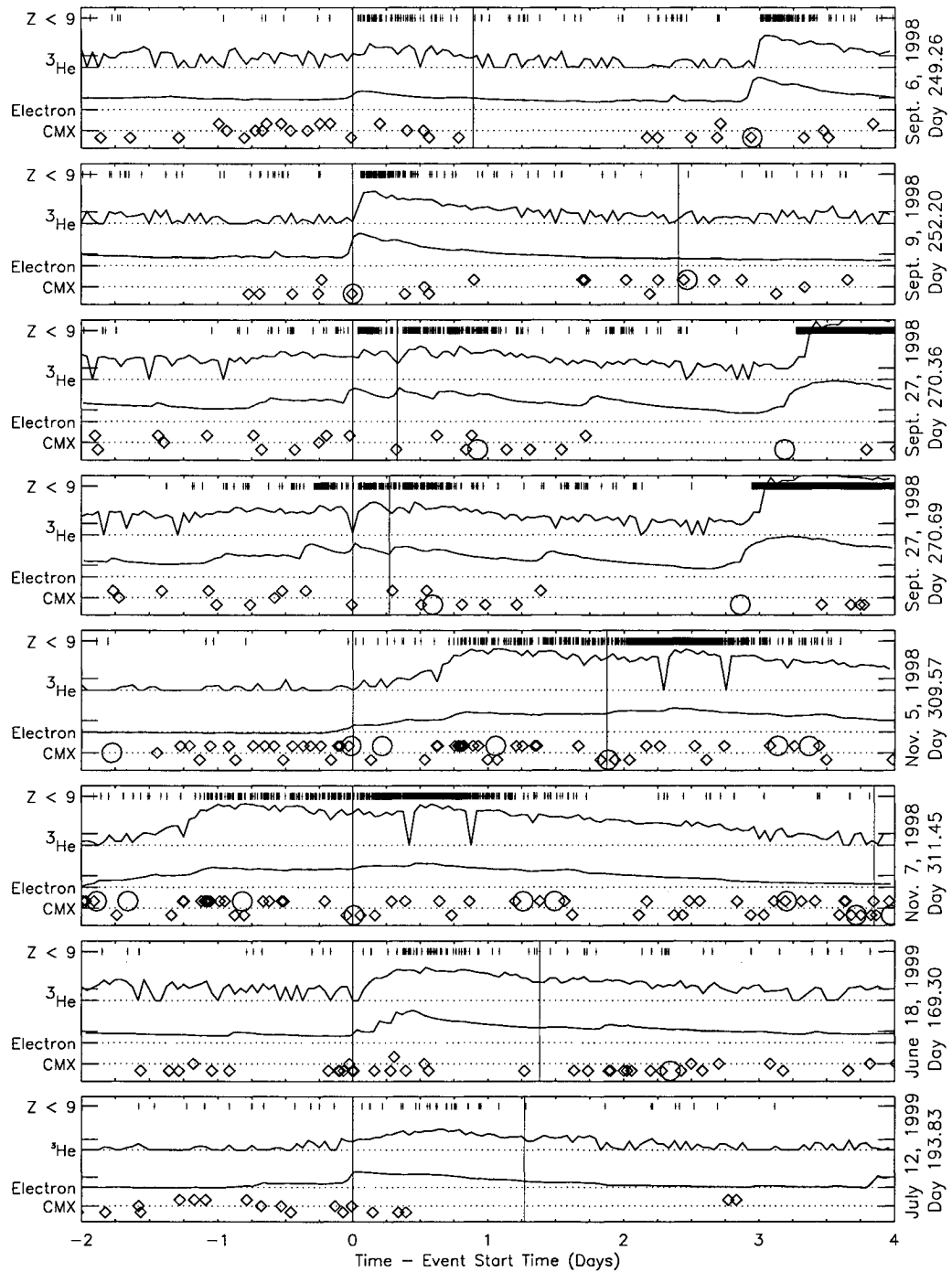


FIGURE 1. The eight events selected for this study. Each panel in the figure represents one event. The event start and stop times are denoted by the two vertical bars. The date of the event onset is noted at the far right side of the panel. The top row of ticks represents the arrival times of heavy nuclei with energy ~ 11 -22 MeV/nucleon. The ^3He trace plot represents the ^3He flux measured using SIS for energy ~ 4.5 -5.5 MeV/nucleon, plotted on a log scale where the first bin on the vertical axis equals one decade. The 38-53 keV electron flux, also shown on a log scale with a one decade indication, was measured using EPAM on ACE. The “CMX” plot represents the incidence of solar X-ray flares which are of C-Class or greater, as measured with the GOES-8 satellite. The diamond symbols denote C-Class flares, and circles M-Class. No X-Class flares were detected during these time periods. X-ray flares which could be associated with an H-alpha flare from the western (eastern) hemisphere of the Sun are shown above (on) the dotted line, while those which could not be associated with an H-alpha flare are plotted below the dotted line.

dent X-ray flares (C, M, and X-Class) and the 38-53 keV electron flux which has been provided by the Electron, Proton, and Alpha Monitor (EPAM) on ACE. The list of X-ray flares has been extracted from a GOES satellite database (<http://www.sel.noaa.gov/index.html>) at the NOAA Space Environment Center. Where possible, the X-ray flares have been associated with an H-alpha flare originating from a known location. The X-ray events in Figure 1 are therefore separated according to east, west, and unknown longitudinal origin on the Sun.

All eight of the events in Figure 1 have C or M-Class X-ray flares ≤ 2 hours before the onset time. If one assumes that the X-rays and energetic nuclei associated with a SEP event depart from the Sun simultaneously, then the minimum difference in transit times for X-rays and 5.5 MeV/nucleon ^3He over 1 AU is ~ 1.2 hours. However, such an assumption is not clearly justified and could be a significant source of uncertainty in calculating expected X-ray flare onset times. Furthermore, because the eight events in this study are relatively small it is frequently difficult to determine their onset times to within $\lesssim 1$ hour. Due to these two sources of uncertainty, and because of the abundance of X-ray flares shown in Figure 1, it is clearly difficult to deduce a unique association between the X-ray emissions and the ^3He -rich events. Therefore it is possible, but not definite, that these eight events are associated with X-ray flares.

Also shown in Figure 1 are the coincident electron fluxes, measured using EPAM. All of the events show increases in the electron flux within $\lesssim 2$ hours of the event onset time. The average difference in transit times for 38-53 keV electrons and 5.5 MeV/nucleon ^3He over a distance of 1 AU is ~ 1.1 hours. However, for the reasons stated above, the expected onset time of the electron flux relative to the ^3He flux is not well determined, and should not be used as a rigid criterion for correlation. Instead the apparent association can be seen by inspecting the electron fluxes at or very near the event onset times in Figure 1.

To classify these eight events further, the heavy element content has been investigated, as shown in Figure 2. In the figure, 17 average abundance ratio enhancements are plotted for the eight SEP events studied here, and are compared with those found by Reames et al. (4) in a study of 228 impulsive SEP events with the ISEE-3 spacecraft. The abundance ratio enhancements are defined relative to coronal values (9). From the figure it is clear that similar abundance enhancements are present in the two data sets. In this comparison it should be noted that the energy interval measured using ISEE-3 is 1.9-2.8 MeV/nucleon, somewhat lower than the ~ 11 -22 MeV/nuc in this study. In addition, while there have been many ^3He -rich events measured by SIS, most do not have large enhancements of heavy elements ($Z \geq 6$) in the energy interval ~ 11 -

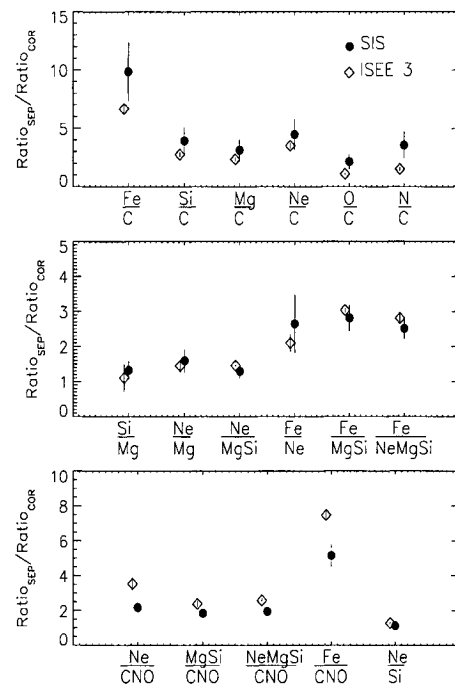


FIGURE 2. Average heavy element abundance ratios, normalized to coronal values, for the eight SEP events occurring between September 6, 1998 and July 12, 1999. Uncertainties in the ratios are statistical in nature, and are shown with one standard deviation.

22 MeV/nucleon. Consequently the ISEE-3 impulsive event sample is much larger than that of SIS.

The background contribution to the heavy element fluxes has been estimated using selected days of solar quiet time from three consecutive time periods. Between May 25, 1998 and November 13, 1998, 59 days of quiet time have been selected. From November 14, 1998 through July 22, 1999 there were 133 days of quiet time, and from July 23, 1999 through October 31, 1999 there were 60 days. Quiet times are defined by imposing a threshold on the He and O fluxes in the lowest three energy ranges of SIS. The thresholds are chosen such that the average O flux is less than 2×10^{-5} particles/(cm 2 Sr sec MeV/nucleon) for the energy interval 7.1-15.6 MeV/nucleon, and the average He flux is less than 1×10^{-4} particles/(cm 2 Sr sec MeV/nucleon) for 3.4-7.3 MeV/nucleon. This definition of solar quiet time is driven primarily by the He flux.

Also of interest in observing ^3He -rich SEP events is the possibility of a correlation between $^3\text{He}/^4\text{He}$ ratios and heavy element abundances. Such a correlation could place important restrictions on acceleration models for this type of event. Recent results by Ho et al. (10) report a correlation between the Fe/C and $^3\text{He}/^4\text{He}$ ratios, using data from the ULEIS instrument on ACE. Past investigations (11, 4) have not found a correlation between heavy

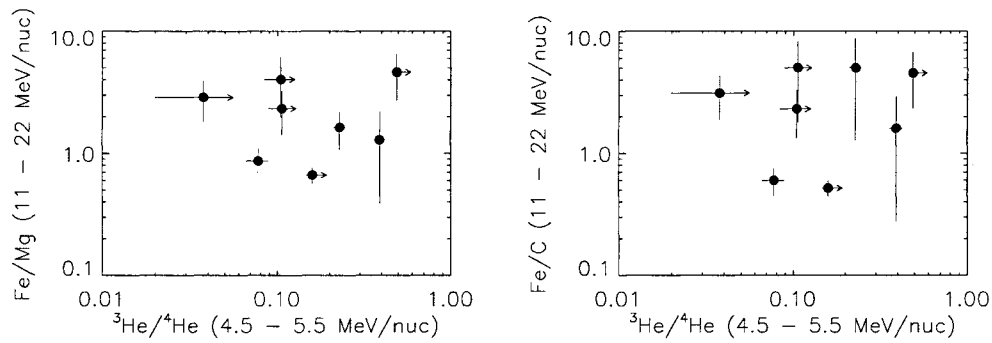


FIGURE 3. Plot of Fe/Mg (left panel) and Fe/C (right panel) against the $^3\text{He}/^4\text{He}$ ratio, for the eight events in this study.

element abundance ratios and $^3\text{He}/^4\text{He}$ ratio, but these studies have been limited to $^3\text{He}/^4\text{He}$ ratios $\gtrsim 0.1$ and have been at somewhat higher energies than the ULEIS measurements. The results by Ho et al. included events with $^3\text{He}/^4\text{He}$ ratios as low as 0.01. In a search for similar correlations using SIS, two heavy element ratios have been plotted as a function of $^3\text{He}/^4\text{He}$ ratio. The left panel of Figure 3 shows the Fe/Mg ratio plotted against the $^3\text{He}/^4\text{He}$ ratio, while the right panel depicts the Fe/C ratio as a function of $^3\text{He}/^4\text{He}$ ratio. In the Fe/Mg plot, there does not appear to be a correlation with the $^3\text{He}/^4\text{He}$ ratio. Similarly, the Fe/C plot does not show a correlation with the $^3\text{He}/^4\text{He}$ ratio, although this is difficult to determine without extending the $^3\text{He}/^4\text{He}$ measurements lower than the 4% limit possible with the SIS instrument in this energy range.

Measurement of the $^3\text{He}/^4\text{He}$ ratio is limited by several contributing factors. As mentioned above, the SIS instrument is not sensitive to ratios lower than $4 \pm 1\%$ in the energy range 4.5-5.5 MeV/nucleon, due to spillover contamination to the ^3He peak from the ^4He peak. A correction for this contribution to the $^3\text{He}/^4\text{He}$ ratio has been applied to the data shown in Figure 3. It should also be noted that no uncertainty has been added to account for contributions to the ^4He from neighboring SEP events. Therefore, the $^3\text{He}/^4\text{He}$ ratios in Figure 3 should be interpreted as lower limits where indicated.

SUMMARY

The heavy element content of these eight ^3He -rich events has been examined. The enhancements of Fe, Mg, Ne, and Si, which are standard indications as to the nature of the material which is present, are consistent within statistical and experimental limitations with the previous study of 228 impulsive SEP events by Reames et al. (4)

There does appear to be an association between electron emission and the onset of these events, which suggests that the events may be impulsive. This is also supported by the presence of X-ray flares at the event onsets, although the frequent occurrence of small X-ray events

hinders any direct correlation. To combat this difficulty, future work may include studies of heavy ion velocity dispersion as a tool to extract the expected X-ray flare onset times. The combination of heavy element content, electron flux association and X-ray emission suggests that these eight events may be impulsive SEP events as defined by previous studies.

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